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On the Determination of Flow Stress Using Bulge Test and Mechanical Measurement

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Abstract. The standard uniaxial tensile test is a widely accepted method to obtain relevant properties of sheet metal materials. These fundamental parameters can be used in numerical modeling of sheet forming operations to predict and assess formability and failure analysis. However the range of strain obtained from tensile test is limited and therefore if one will need further information on material behavior, extrapolation of tensile data is performed. The bulge test is an alternative to obtain ranges of deformation higher than tensile test, thus being possible to obtain non-extrapolated data for material behavior. Several methods may be used to obtain stress-strain data from bulge test, but a common concept is behind them, which needs the measurement of bulge pressure, curvature of bulge specimen, its thickness at the pole and the application of membrane theory. Concerning such measurements, optical methods are being used recently but classical mechanical methods are still an alternative with its own strengths. This paper presents the use and development of a mechanical measuring system to be incorporated in a hydraulic bulge test for flow curve determination, which permits real-time data acquisition under controlled strain rates up to high levels of plastic deformation. Numerical simulations of bulge test using FEM are performed and a sensitivity analysis is done for some influencing variables used in measurements, thus giving some directions in the design and use of the experimental mechanical system. Also, first experimental results are presented, showing an efficient testing procedure method for real time data acquisition with a stable evaluation of the flow curve.

Keywords: Flow stress determination, Bulge test, Sheet metal forming.
PACS: 81.70.Bt

INTRODUCTION

The hydraulic bulge test is used in the determination of strain hardening properties of sheet materials in biaxial tension. In the bulge test, stress and strain can be obtained up to failure of the specimen, while in the conventional uniaxial test, only the uniform strain range can be utilized. Since the strains in stamping are normally larger than the uniform strain, the bulge test can better describe the plastic properties of sheet metal at large strains.

Although different methods are being used, when obtaining the stress-strain data from bulge test, a common concept exists, which involves the need of the continuous measurement of some bulge variables and the use of membrane theory. The needed bulge variables are the bulge pressure, the curvature of bulge specimen and its thickness at the pole. Bulge pressure is obtained directly from bulge machine, while curvature and thickness data may have different procedures for its evaluation. A simplified approach may involve indirect methods by estimations of curvature or thickness based in analytical equations [1, 2]. Direct methods make use of continuous data acquisition of bulge geometry to evaluate such variables and two groups may be seen: optical and mechanical methods. Optical methods include a continuous strain analysis during the forming process with a CCD-camera device in combination with videogrammetic software [3, 4], while mechanical systems uses physical tactile devices, thus permitting data acquisition to evaluate thickness and curvature [5, 6].

The system for data acquisition presented in this paper uses a mechanical system, which permits a continuous evaluation of pressure, evaluation of specimen curvature by a spherometer device and thickness evaluated by specimen in-plane deformation using an extensometer device.

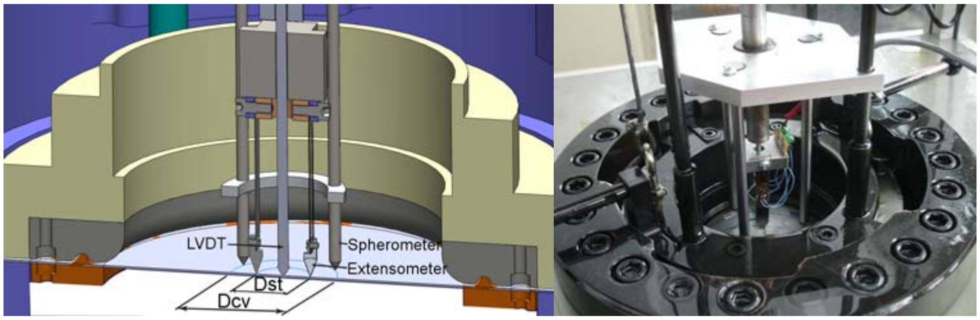


FIGURE 1. Virtual and real image of the mechanical system for bulge test data acquisition.

Figure 1 shows a representation and a picture of bulge machine with fundamental components of data acquisition system. Corresponding die has an opening diameter of 150 mm and a die profile radius of 13 mm, uses blanks of 200 mm, which are clamped during testing.

THEORY FOR STRESS AND STRAIN MEASUREMENT

In order to determine stress-strain data, analysis of measurable parameters from bulge test must be performed. For this purpose, membrane theory is commonly used for determination of flow stress curve. Due to small sheet thickness/bulge diameter ratio, bending stresses are neglected in this theory, and consequently it can only be applied to thin sheets. Thus, considering that through thickness stress σ_3 is zero, a relation between stresses, sheet geometry and bulge pressure can be established:

$$\frac{\sigma_1}{R_1} + \frac{\sigma_2}{R_2} = \frac{p}{t} \tag{1}$$

where σ_1 and σ_2 are the principal stresses on sheet surface, R_1 and R_2 are the corresponding radius of the curved surface, p is the hydraulic pressure and t is the sheet thickness. Considering the axisymmetric case of bulge test, both principal stresses can be taken equivalent and equal to the so-called membrane stress (σ_1=σ_2=σ). The same reason can be pointed out to curvature radius, R_1 and R_2, which also remain equivalent (R_1=R_2= R_b), whatever plane is considered. Therefore, Equation 1 can be simplified and flow stress can be determined by:

$$\sigma = \frac{p \cdot R_b}{2 \cdot t} \tag{2}$$

As it can be seen, determination of flow stress requires calculation of curvature radius R_b and current sheet thickness t at the top of the dome during testing. For calculation of curvature radius, one can show that curvature radius can be obtained by a simple geometrical construction, which is given by the following equation:

$$R_b = \frac{\left(D_{CV}/2\right)^2 + h^2}{2 \cdot h} \tag{3}$$

where $Dcv/2$ is the spherometer radius and h is the dome height, measured from the tripod pins (Fig. 2). This relation is only valid if a spherical dome is considered within spherometer radius region. For the evaluation of current sheet thickness t, measurement is done with initial sheet thickness t_0 and the current thickness strain ε_t , as:

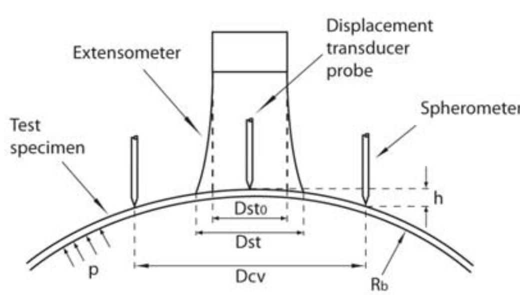


FIGURE 2. Variables used for the evaluation of stress and strain.

$$t = t_0 \exp(-\varepsilon_t) \tag{4}$$

The thickness strain ε_t is calculated by evoking the assumption of material incompressibility. If the volume remains constant during plastic deformation, the relation

$$\varepsilon_t = -(\varepsilon_1 + \varepsilon_2) \tag{5}$$

is verified, where ε_1 and ε_2 are the principal plastic strain components on sheet surface. As for stresses and curvature radius, the hypothesis of equal values for both surface strains near the pole is assumed and strain in thickness direction is given by:

$$\varepsilon_t = -(\varepsilon_1 + \varepsilon_2) = -2\varepsilon \tag{6}$$

where ε is the membrane strain. The determination of this value is performed by measuring the expansion of a circle with an initial diameter of D_{st0}. This measurement is done by a modified extensometer device, with two probes that rest in the test specimen, initially positioned onto the initial circle. During testing, this circle expands, without change of volume, to a diameter D_{st} and current thickness strain can be calculated as:

$$\varepsilon_t = 2\log_e\left(\frac{D_{st0}}{D_{st}}\right) \tag{7}$$

Above expressions will be used for evaluation of stress-strain curves presented in this paper. As for thickness and radius of curvature evaluation, besides the use of Equation 4 and 3, alternate evaluations will be presented in the numerical modeling section. These alternate evaluations will be called *local thickness* and *local radius of curvature*, while those based from Equations 4 and 3 will be called *extensometer thickness* and *spherometer radius of curvature*. The evaluation of *local thickness* is based in distance between upper and lower nodes of blank. For the local radius of curvature the evaluation method follows the determination of the second derivative of the geometry, based in finite difference method using the central point and its neighbors, by considering unequally spaced points [7].

NUMERICAL MODELLING

Main objectives of performing numerical modeling of bulge test are the study of evolution of fundamental variables and sensitivity analysis of results to parameters used by mechanical system.

Evolution study includes variables like thickness and curvature, while sensitivity analysis uses different diameters *Dst* and *Dcv* (see Fig. 1 or 2) to weight the accuracy of results when obtaining the flow curve of tested material.

Numerical simulation of bulge test is performed with Abaqus/Explicit by using 3046 3D solid 8 node elements with reduced integration (C3D8R) and two layers along thickness. Due to symmetry, only one quarter is modeled. The upper tool in contact with blank is also modeled, using 6080 3D rigid 3 node elements (R3D3 from Abaqus library).

The blank is modeled as a von Mises elastic-plastic material with a Young's modulus of 206 GPa, the Poisson's ratio of 0.3 and an initial yield stress of 175 MPa. The isotropic hardening is described by piecewise linear segments matching a power law with k=465 MPa and n=0.21. Initial sheet thickness is 1.0 mm. Figure 3 shows the numerical model and the equivalent plastic strain contour for a bulge height of 40.2 mm.

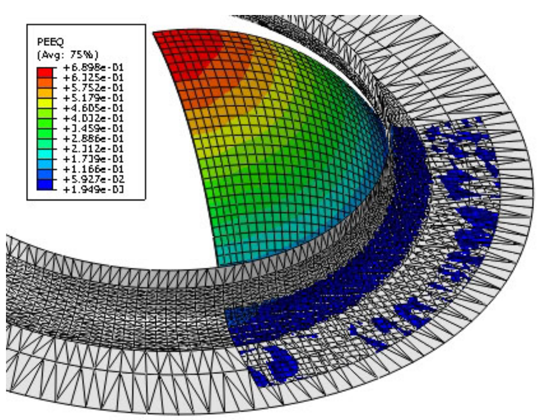


FIGURE 3. Analysis model for numerical modeling with contour of equivalent plastic strain.

Thickness and Curvature Evolution From Pole to Periphery

When using bulge mechanical device, stress and strain are evaluated using, respectively, Equations 2 and 7. Main variables for this evaluation like radius of curvature and thickness are obtained from spherometer and extensometer mechanical devices. Due to these variables and corresponding values being related to diameters *Dcv* and *Dst*, it is important to understand how they change from pole to periphery of bulge.

As shown in Fig. 4, the qualitative tendency for thickness is to increase from pole to periphery. This experimental evidence will, as a consequence, give different strain results when considering different points along the section or when using different diameters *Dst* for strain evaluation. A similar tendency is observed with radius of curvature having smaller radius of curvature for pole when compared to periphery.

Quantitative results for this tendency are shown in Fig. 5 and 6. For each variable, thickness or radius of curvature, two kinds of results are presented: a so-called local result (thickness or radius of curvature – see section "theory for stress and strain measurement") and the result as obtained by mechanical device (spherometer or extensometer) by using Equations 3 and 4.

Variation of thickness is presented in Fig. 5 for different bulge heights. As bulge height evolves, thickness differential between pole and periphery is increasing. When comparing thickness evaluated locally and by extensometer method it is seen the smoothing of curves obtained by this last method.

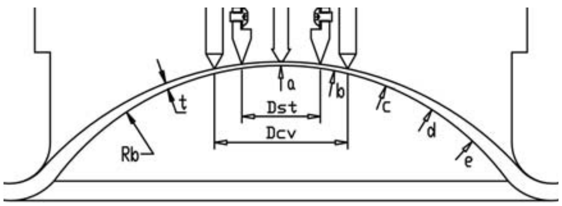
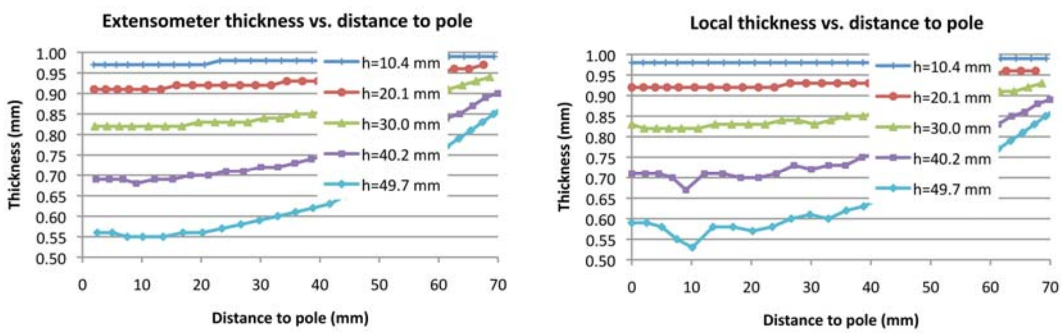
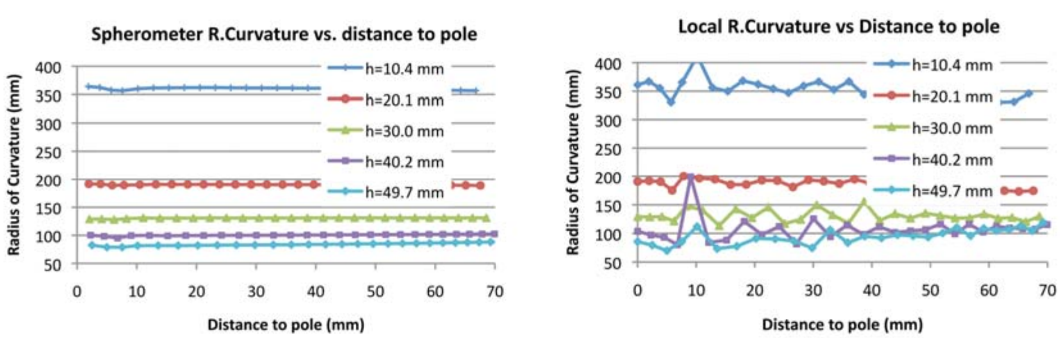


FIGURE 4. Model showing the variation of thickness from pole to periphery and defined variables.



(a) (b)

FIGURE 5. Thickness variation from pole to periphery for different bulge heights; (a) extensometer method (b) local evaluation. (h-pole height).



(a) (b)

FIGURE 6. Curvature variation from pole to periphery for different bulge heights: (a) spherometer method (b) local evaluation. (h-pole height).

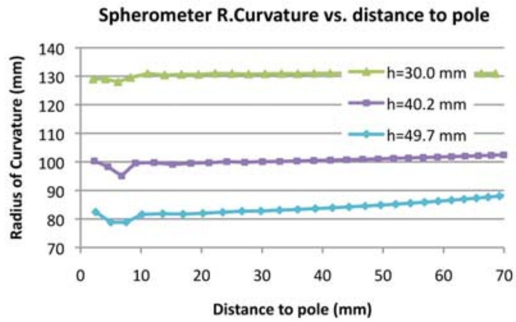


FIGURE 7. Curvature variation from pole to periphery is more evident for higher bulge heights.

Variation of radius of curvature from pole to periphery for different bulge heights is presented in Fig. 6. As seen, the local evaluation of curvature gives quite large oscillations along the nodes of the section, from pole to periphery. Similar observation of oscillations for this variable exists when experimental optical methods are used [3, 8], since the points on the surface of the bulge blank, used for optical evaluation, have a similar behavior to nodes. A. Guner [8] even states that calculated radii of curvature have larger oscillations than the ones obtained from simulations, due to the lower resolution of the optically measured geometry when compared to simulated geometry.

The same curvature result is quite smooth when evaluated by spherometer method, Equation 3, as seen in Fig. 6(a). Since this method uses only two points for such evaluation, this means that calculated radius of curvature will be approximated by a circle, thus giving a more global result, rather than a local one.

Concerning the trend of variation for radius of curvature, only at higher pole heights we may observe increasing radius of curvature from pole to periphery. Figure 7 shows, with more evidence, such variation when bulge pole height is 49.7 mm.

Study on Using Different Diameters to Evaluate Strain and Curvature

The bulge experimental mechanical system evaluates strain and curvature having the possibility of using different diameters for such evaluation. The study in this section intends to understand the influence on obtained results when using different diameters. For this study, there is a reference for the flow curve to be obtained, which is the one given as input for the simulation code, being also the one obtained as output for the equivalent stress and equivalent strain for the element at the pole.

The curvature is evaluated using *Dcv* diameter (see Fig. 1, 2 or 4), while strain is evaluated using *Dst* diameter. The study consists of changing one of these diameters while the other is being kept constant. The constant diameter has been defined a value of 25 mm, since this is a reference diameter for flow curve determination using bulge test [3, 5, 8].

Figure 8 shows results obtained when curvature is evaluated using a constant *Dcv* diameter (*Dcv*=25 mm) and strain is evaluated using different *Dst* diameters, *Dst* ranging from 15 to 66 mm. As seen, different evaluated flow curves are obtained some of them above the reference (smaller *Dst* diameters) and other curves below the reference

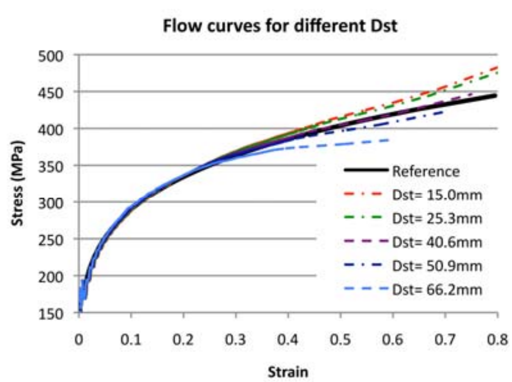


FIGURE 8. Flow curves when *Dcv* =25mm and different *Dst* for evaluation of strain.

(larger *Dst* diameters). Scatter of such results begin at about 0.3 strain and the best results are obtained for a *Dst* diameter close to 40 mm (*Dst*=40 mm and *Dcv*=25 mm).

When changing curvature evaluation diameter, *Dcv*, while keeping constant the strain evaluation diameter (*Dst*=25 mm), the results are those of Fig. 9. Now, evaluated flow curves begin to deviate at 0.2 strain, except for *Dcv*=15 mm which begins at about 0.5 strain. All evaluated flow curves are now above the reference curve.

Keller [3] made a similar parametric study and its results have similar tendency. Such results are obtained from experiments using optical methods, thus confirming this observed trend with current numerical results.

As a complement, the plot of flow curves obtained for different points (elements) along the bulge section from pole to periphery are presented in Fig. 10. Corresponding points are defined in Fig. 4 as *a*, *b*, *c*, *d* and they are located at increasing distances to pole, as presented in Fig. 10.

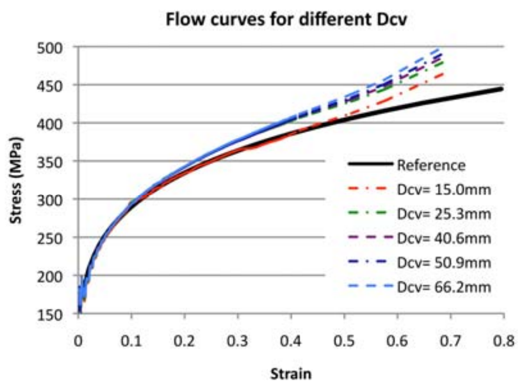


FIGURE 9. Flow curves when *Dst*=25mm and different *Dcv* for evaluation of curvature.

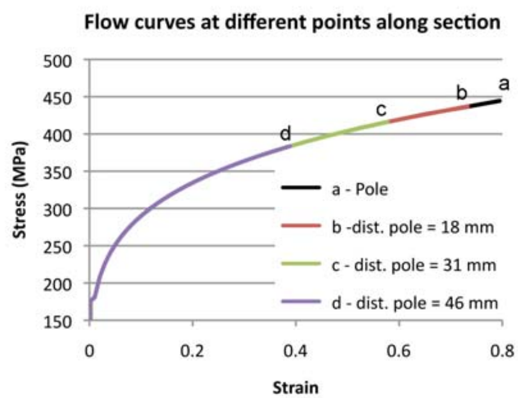


FIGURE 10. Flow curves for different points (obtained from elements) at increasing distances to pole.

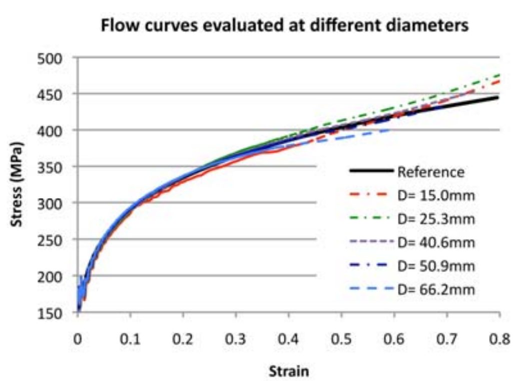


FIGURE 11. Flow curves when using the same diameter for strain and curvature evaluation (*Dst*=*Dcv*).

All these curves are coincident, they represent the evolution of flow curves, up to the same bulge height and their differentiation is due to different limiting strain attained by each point. The pole attains a limiting strain of 0.8, while a point located at 46 mm from pole attains a limiting strain of 0.5. Therefore, points located at increasing distances to pole have lower strains (lower reduction of thickness, see Fig. 4), but the evolution of stress to strain (flow curve) is the same for every point. This also shows that a correct method to obtain the flow curve from bulge test would be the use of the same point to obtain both the strain (extensometer) and the curvature (spherometer), which means that diameter *Dst* should be the same or as close as possible to diameter *Dcv*.

With this guideline in mind, new results were tested to evaluate flow curve for different diameters but now diameter *Dst* having the same value as diameter *Dcv*. Corresponding results are shown in Fig. 11. Now, evaluated flow curves are closer to the reference, except for 15 mm and 66 mm, being almost totally coincident for a diameter of 50 mm.

EXPERIMENTAL RESULTS

A first prototype of a mechanical system has been developed, which gave the way to a new prototype being now at its final steps of development. Results obtained with first prototype are being presented to show the possibilities of the system.

One of the most sensitive results to be obtained is related with curvature evaluation. As seen in Equation 2, any inaccuracy or any oscillation in evaluation of radius of curvature will influence directly the evaluation of stress. Therefore, preliminary tests were performed in order to validate the data acquisition of curvature. Several bulge geometries obtained from different bulge heights were measured by using a CMM (Coordinate Measuring Machine) and corresponding curvatures evaluated. Such discrete points were then compared with data obtained from developed spherometer and bulge data acquisition system and results are compared in Fig. 13. As seen, corresponding points are very much coincident, thus validating the data acquisition system.

First flow curve obtained with developed system is presented in Fig. 14. Stress and strain data points are evaluated from real time data acquisition, the strain evaluated from the extensometer and the curvature/stress from spherometer. A key point is the obtained flow curve being very stable, no significant oscillations being observed,

FIGURE 12. CMM Measurement of bulge specimens for different bulge pressures.

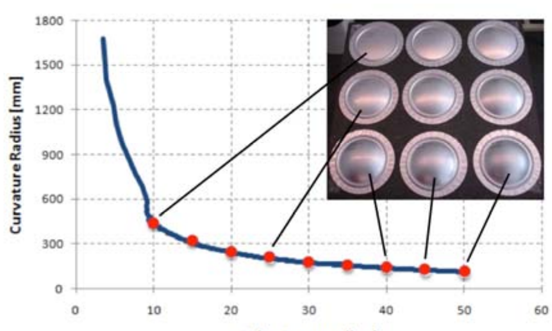


FIGURE 13. Curvature evolution with bulge pressure; comparison between curvature calculated by the spherometer device and curvature measured by a CMM, for several discrete bulge pressures.

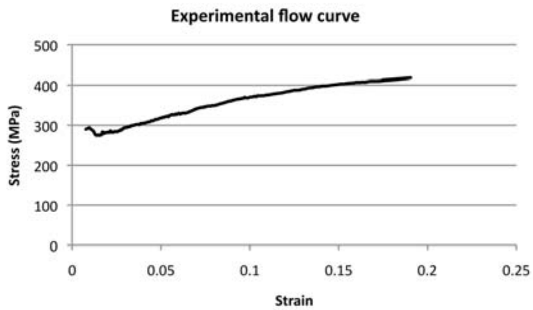


FIGURE 14. Current results for flow curve with real time data acquisition, using developed mechanical system.

from this real-time data acquisition. This stability gives the assurance and the possibility of controlling the bulge machine, in order to obtain a constant strain rate test, an important point when testing and evaluating the flow curve for some materials.

CONCLUSIONS AND PERSPECTIVES

A measuring system has been developed and incorporated in a hydraulic bulge test machine in order to obtain data for flow curve evaluation and material characterization. First results show an efficient testing procedure for real time data acquisition and a stable and smooth evaluated flow curve.

Numerical results have been presented, which show the trends for flow curves evaluation, using different diameters for strain measurement and curvature measurement. Better results are obtained when using the same diameter for both measurements. For current bulge diameter of 150 mm, a measurement diameter of 50 mm is suggested, when using current equations for stress and strain evaluation.

Future developments will include experimental testing to validate observed trends in numerical results, additional numerical studies for different materials with different strain hardening and anisotropy, the design and development of a different version of the mechanical system, which will follow directions from numerical studies, including needed robustness to support material testing up to its fracture.

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